

Hydrogen Refueling System Based on Autothermal Cyclic Reforming

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ABSTRACT

GE Energy and Environmental Research Corporation (GE-EER) is developing a hydrogen generation system designed for vehicle refueling. The hydrogen generation system uses a proprietary reformer to convert fuels to a hydrogen-rich gas that can be easily purified. The Autothermal Cyclic Reforming (ACR) process is a unique technology that can be applied for the production of hydrogen or syngas from many fuels, including natural gas, diesel fuel, coal, and renewable feed-stocks, such as biomass. The system also includes a Pressure Swing Adsorption (PSA) unit to purify the hydrogen, a hydrogen compressor, high-pressure storage tanks, and a dispensing unit to safely deliver the hydrogen from the storage tanks to the hydrogen vehicle. Praxair will develop the PSA unit, the hydrogen compressor and hydrogen storage tanks. HCl will develop the hydrogen dispenser. BP will analyze the refueling station logistics and safety.

An optimal process configuration was selected, process flow diagrams were developed, and efficiencies were calculated. A detailed analysis was conducted to compare high-pressure and low-pressure reforming configurations.

In collaboration with an ongoing DOE project, "Fuel Processing Based on ACR for Stationary PEM Fuel Cells", Contract No. DE-FC02-97EE50488, the component design of the fuel processor has been completed and the system is being fabricated. The fabrication is expected to be complete by July 2002.

A detailed safety analysis including Personnel Hazard Assessment (PHA), Hazardous Operation (HAZOP) analysis, and Failure Mode and Effects Analysis (FMEA) has been performed.

An economic analysis for the hydrogen refueling station is being performed. The installed capital costs for 150 kWt and 500 kWt (thermal) commercial hydrogen generators were estimated from the current cost of the prototype hydrogen generator. The cost of H₂ was projected to understand the market position of ACR-based hydrogen generator.

INTRODUCTION

System Description

Autothermal Cyclic Reforming (ACR) is an autothermal cyclic steam reforming technology for converting hydrocarbons to a hydrogen-rich stream. The ACR process operates in a three-step cycle that involves steam reforming of the fuel on a Ni catalyst (Reforming Step), heating the reactor through oxidizing the Ni catalyst (Air Regeneration Step), and finally reducing the catalyst to its original state (Fuel Reduction Step) as shown in Figure 1. The heat required for the endothermic reforming reaction is provided during the exothermic oxidation of Ni to NiO.

A simplified process flow diagram of the entire hydrogen generating and dispensing system is shown in Figure 2. The hydrogen-rich syngas generated in the Autothermal Cyclic Reformer is fed to a Low Temperature Shift (LTS) reactor in which the carbon monoxide reacts with steam to form carbon dioxide and additional hydrogen. The gas is then cooled to condense the water. The syngas is purified in a Pressure Swing Adsorption (PSA) system. The PSA delivers high purity hydrogen to a compression / storage system where it is pressurized to the desired level and stored. A dispenser system is used to safely fill the hydrogen-powered vehicle.

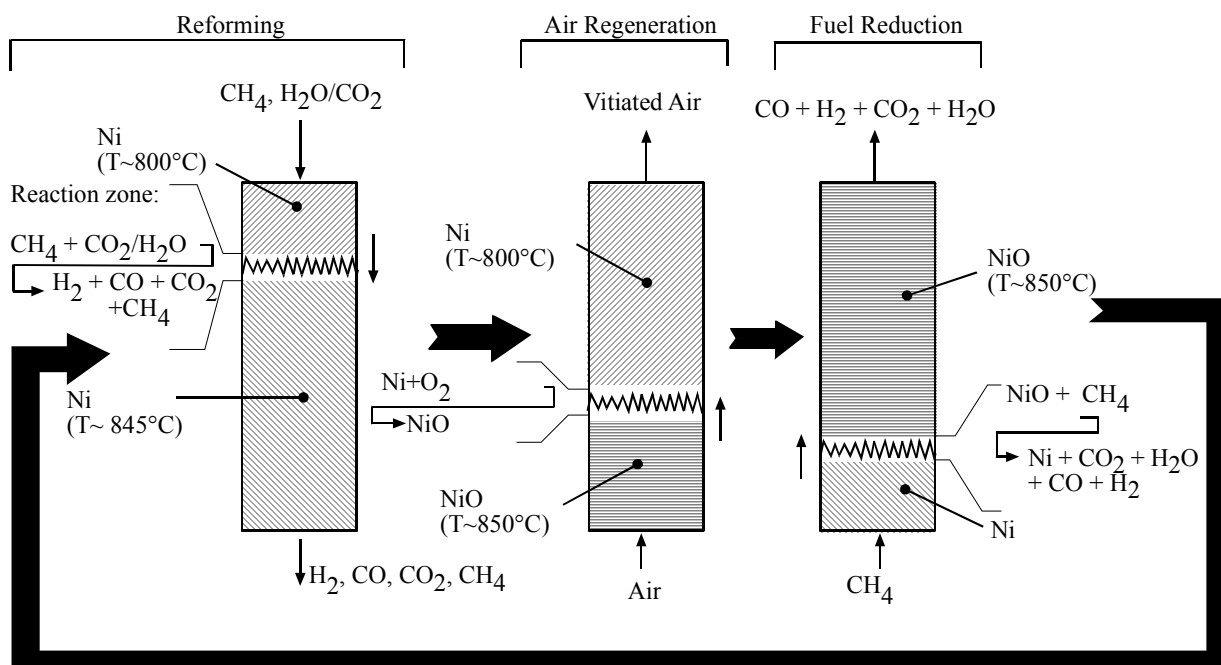


Figure 1 - Illustration of the Autothermal Cyclic Reforming (ACR) process.

Project Goals and Objectives

The overall technical objective of the project is to design, fabricate and install a reliable and safe H₂ refueling system, based on GE's patented Autothermal Cyclic Reforming (ACR) process. The system will be capable of producing at least 40 kg/day of H₂ (sufficient for refueling at least 1 bus or 8 cars per day). The target cost of H₂ is less than \$2.50/kg based on a natural gas price

of \$4.00/MMBtu, when the H₂ refueling system is manufactured at a rate in excess of 1,000 units/year. The program is being conducted in 3 phases. The objective of Phase I (2002) is to design the integrated system and to assess the technical and economic feasibility of the design. The objective of Phase II (2003-4) is to perform subsystem development, and the goal of Phase III (2004-5) is to demonstrate the fully integrated system. GE-EER will develop the reformer and integrate the full system. Praxair will develop the PSA unit, the H₂ compressor and H₂ storage tanks. HCI will be responsible for the H₂ dispenser. BP will analyze the refueling logistics and safety.

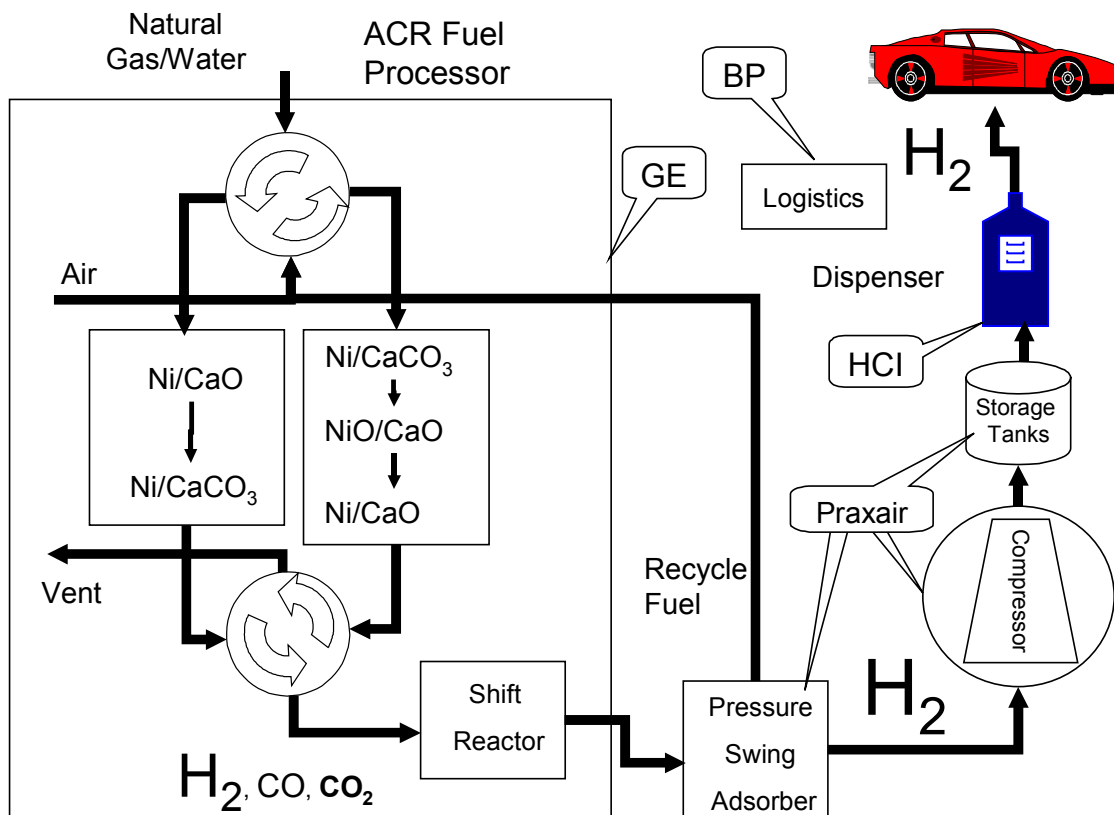


Figure 2 - Integrated Hydrogen Generating and Dispensing System.

DISCUSSION

The progress in the project is described below.

Process Analysis

The efficiency of the hydrogen generator, based on Higher Heating Value (HHV), is defined as the ratio of the HHV of the hydrogen produced divided by the HHV of the fuel (natural gas) consumed. The hydrogen generator includes the reformer, steam generator, LTS reactor, PSA

and the recycle stream from the PSA to the reformer. The fuel consumed must include any supplemental fuel used in the process to generate heat and/or steam.

$$\text{Efficiency of } H_2 \text{ Generator} = \frac{\text{HHV Pure } H_2 \text{ Produced}}{\text{HHV of Fuel Consumed}}$$

The efficiency expressed only in terms of HHV of hydrogen produced and fuel consumed does not account for the effect of parasitics, such as compression work and heat loss.

A preliminary process analysis of the hydrogen generator, which includes the reformer, steam generator, LTS reactor, condenser and PSA, has been completed. The PSA requires that the reformat be delivered to it at 7.9 bar (100 psig). A detailed analysis was conducted of high-pressure and low-pressure reforming configurations. In the high-pressure reforming configuration, the feed fuel is compressed to 7.9 bar, and the reforming step is operated at a high pressure of 7.9 bar. In the low-pressure reforming configuration, the reforming step is operated at a low pressure of 1.5 bar, and the syngas is compressed to 7.9 bar just upstream of the PSA. In both configurations the air regeneration step is operated at atmospheric pressure and hence has minimal compression requirements.

The major factors affecting the efficiency are: 1) the conversion in the reformer and LTS reactors, 2) the recovery of hydrogen in the PSA, 3) the utilization of the process heat to generate the process steam, and 4) the minimization of parasitic losses.

Since the thermal integration of the system has a significant impact on the efficiency, several heat exchanger configurations were considered for both the high pressure and the low pressure configurations. Pinch analysis in the heat exchangers was conducted, in order to optimize the thermal integration of the system.

Table 1 shows the results for the high pressure and low pressure configurations. The operating conditions for the PSA are 7.9 bar and 50°C with 80% hydrogen recovery. The table shows the ratio of hydrogen produced to fuel fed, the efficiency (excluding parasitic losses) and the electricity consumed in the compressors as a percentage of the HHV of fuel.

Table 1 shows that if the parasitic losses are not included, the low-pressure configuration achieves higher efficiency than the high-pressure configuration. However, the low-pressure configuration requires higher compression work. To determine which configuration is better, a detailed economic analysis will be conducted taking into account the efficiency, compression work, cost of natural gas, cost of electricity and capital costs of both configurations.

Table 1: ACR Process Efficiency: High-Pressure and Low-Pressure Reforming Configurations

	High-Pressure Configuration	Low-Pressure Configuration
H ₂ Recovery in PSA	80%	80%
Electricity Consumed / HHV of fuel	1.0%	4.4%
Mol H ₂ Produced / Mol Fuel Fed	2.50	2.66
Efficiency (Excluding Parasitics) = HHV of H ₂ Produced / HHV of Fuel Fed	80.1%	85.2%

Fabrication of Prototype Fuel Processor

In collaboration with other ongoing DOE project “Fuel Processing Based on ACR for Stationary PEM Fuel Cells”, Contract No. DE-FC02-97EE50488, the component design of the 150 kW (HHV) hydrogen generator has been completed. Fabrication and installation of the major subsystems of the prototype (reformer reactor, LTS reactor, steam generator and condenser) have been completed (see Figure 3). The component design will be modified for hydrogen refueling applications, based on input from Praxair on integration of the PSA.



Figure 3 - Autothermal Cyclic Reformer.

Safety Analysis and Permitting

A detailed safety analysis including Personnel Hazard Assessment (PHA), Hazardous Operation (HAZOP) analysis, and Failure Mode and Effects Analysis (FMEA) has been performed. An analysis of safety and permitting has been initiated, to ensure that the system is compliant with all applicable building, fire and electrical codes. Required documentation will be submitted to obtain permits for system operation.

Economic Analysis

Preliminary economic estimates are presented here for the costs of a hydrogen production and refueling system that is not mass produced. A more detailed cost analysis will be conducted to estimate the cost of the mass produced system.

The analysis started with available information on the installed capital cost for the 150 kW prototype hydrogen generator. Scaling laws were used to determine the cost of the commercial system from the cost of the prototype unit, since as more units are built the cost is expected to decrease. As part of the economic analysis task, the installed capital costs for 150 kW and 500 kW commercial fuel processors were estimated. Finally the cost of H₂ was estimated in order to understand the market position of ACR based fuel processor.

The total installed capital cost includes: 1) equipment cost, 2) design cost, and 3) fabrication cost. For the prototype hydrogen generator, the equipment costs were based on the prototype unit that is shown in Figure 3. For equipment that is not currently installed, such as a PSA, quotes were received from vendors. The major systems in the hydrogen generator are: 1) reformer reactor, 2) LTS reactor, 3) PSA unit, 4) steam generator, and 5) air compressor. The costs for switching valves, pressure switches, controllers and the sampling system were also

included in the equipment cost. It was assumed that the piping and instrumentation accounted for 30% of the total equipment cost. The design and fabrication costs were estimated from GE-EER's previous experience in the area of hydrogen generation. The total installed cost and its breakdown into equipment cost, design cost, and fabrication cost are shown in Table 2.

Table 2 - Estimation of Capital costs for 150kW Hydrogen Generator (excludes cost of hydrogen compressor, storage tanks and dispenser; does not consider mass production).

Cost	150 kW Prototype System	150 kW Commercial System
Equipment Cost	\$350,000	\$332,500
Design Cost	\$90,000	\$45,000
Fabrication cost	\$130,000	\$97,500
Total Installed capital cost	\$570,000	\$475,000

The cost of the commercial hydrogen generator was estimated using scaling laws, since costs are generally expected to decrease as more units are built. It was assumed that the equipment costs of mass-produced units (valves, materials, controls etc.) would decrease by 5% when commercial units are built. As outlined in plant design literature (Ref 1), for specialty equipment such as a PSA unit or a steam generator the design costs reduce by 50% and the fabrication costs reduce by 25% as more and more units are designed and built. Based on these assumptions, the total projected installed cost for the hydrogen generating system reduces from \$570,000 for the prototype system to \$475,000 for the commercial system, as shown in Table 2.

The total installed cost for the commercial 500 kW system was scaled from the total installed cost of the commercial 150 kW system, using the following power law:

$$(\text{Cost of 500 kW system}) = (\text{Cost of 150 kW system}) (500 / 150)^{0.29}$$

Table 3, taken from reference (Ref 3), shows that as a commercial reformer system is scaled from 418 kW of H₂ to 4,180 kW of H₂ the scaling factor is 0.29. It was assumed that the scale factor from 150 kW to 500 kW is also 0.29. This results in an installed capital cost of \$675,000 for a 500 kW commercial hydrogen generator.

Finally the cost of hydrogen generation for a 500 kW commercial unit is presented in Table 4 (excluding the costs of hydrogen compression, storage and dispensing). The net revenue required was determined from the capital investment, operating and maintenance costs, and fuel and electricity costs. The natural gas cost was assumed to be \$4.5/MMBTU, and the electricity cost was assumed to be 8¢/kW.hr. The efficiency of the system (80%) was used to determine the required natural gas to produce 500 kW of hydrogen. Also, a capacity factor of 90% for plant utilization was used. The capital recovery factor was calculated assuming 10% interest rate over 15 years. The cost of H₂ generation was estimated to be \$2.25 /kg (\$16.6/MMBtu). This preliminary cost analysis did not consider the cost reduction due to mass production and did not consider the cost of hydrogen compression, storage and dispensing. These costs are currently being analyzed.

Table 3 - Estimation of scaling power exponents for commercial reformer capital costs (ref 3).

MM SCFD of H ₂	\$/kW	KW of H ₂	Total Capital Cost	Scaling Power Exponent
200	80	835,927	\$ 66,874,155	0.60
20	200	83,593	\$ 16,718,539	0.56
1	750	4,180	\$ 3,134,726	0.29
0.1	4,000	418	\$ 1,671,854	

Table 4 - Estimation of cost of hydrogen generation (excludes cost of compression, storage and dispensing; does not consider mass production).

REFORMER H ₂ GENERATION CAPACITY			500.0	LHV kW
			591.0	HHV kW
CAPITAL INVESTMENT				
Total Plant Cost (TPC)			\$675,000	
Allowance for Funds During Construction (AFDC)	6.3% of TPC		\$42,525	
Total Plant Investment (TPI)			\$717,525	
Royalty Allowance	2.6% of TPI		\$18,656	
Inventory Capital	0.8% of TPI		\$5,740	
Total Capital Requirement (TCR)			\$741,921	
LEVELIZED CAPITAL CARRYING CHARGES (ANNUAL BASIS)				
Capital Recovery Factor	13.1% of TCR			\$97,543
OPERATING AND MAINTENANCE COSTS (ANNUAL BASIS)				
Operating Labor	1.0% of TCR		\$7,419	
Maintenance Labor	0.9% of TCR		\$6,677	
Maintenance material	1.2% of TCR		\$8,903	
Administrative and Support Labor	0.5% of TCR		\$3,710	
Total Operation and Maintenance				\$26,709
SYSTEM EFFICIENCY				
	80%	(HHV)		
FUEL & ELECTRICITY COSTS (ANNUAL BASIS)				
Natural gas feed	22,081.8	MMBtu/year		
Natural Gas cost per year	\$4.5	per MMBtu	\$99,368	
Electricity Required/HHV of Fuel	4.4%			
Electricity Required	284,742.8	kW-hr		
Electricity Unit Cost	8	¢/kW-hr	\$22,779	
Catalysts			\$33,548	
Total Cost of Fuel & Electricity, accounting for capacity factor				\$140,126
NET REVENUE REQUIRED (ANNUAL BASIS)				\$264,378
HYDROGEN GENERATED				48.40
CAPACITY FACTOR				90%
COST OF HYDROGEN				\$16.6
COST OF HYDROGEN				\$2.25

FUTURE WORK AND MILESTONES

During the remaining part of Phase I, the process analysis of the PSA, hydrogen compressor, hydrogen storage tanks, and dispenser will be completed, and the economic analysis will be completed. Also, the development activities and test work that is needed to both validate the design and identify a viable business model for commercialization, within the capital cost target, will be completed. During Phase II, the subsystems will be developed and tested with the objective of achieving the performance goals. During Phase III, the integrated H₂ refueling station will be fabricated, installed and operated.

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LIST OF ACRONYMS

ACR	Autothermal Cyclic Reforming
DOE	Department of Energy
FMEA	Failure Modes and Effects Analysis
GE	General Electric
HAZOP	Hazardous Operation
HCI	Hydrogen Components Inc.
HHV	Higher Heating Value
PEM	Proton Exchange Membrane
PSA	Pressure Swing Adsorption